ACS APPLIED MATERIALS & INTERFACES

Research Article

Cite This: ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

www.acsami.org

# Thermally Activated Delayed Fluorescence in Polymer−Small-Molecule Exciplex Blends for Solution-Processed Organic Light-Emitting Diodes

Piotr Pander,[†] Szymon Gogoc,[‡] Marco Colella,[†] Przemyslaw Data,[†,‡,§] and Fernando B. Dias*[,†]

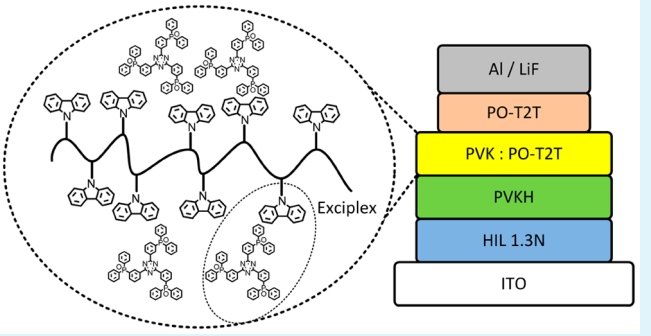
[†]Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom

[‡]Faculty of Chemistry, Silesian University of Technology, Ks. M. Strzody 9, 44-100 Gliwice, Poland

[§]Centre of Polymer and Carbon Materials, Polish Academy of Sciences, M. Sklodowskiej-Curie 34, 41-819 Zabrze, Poland

Supporting Information

**ABSTRACT:** The photophysics of an exciplex state formed between a small molecule and a polymer is investigated in this work. The results obtained with this blend show the strong potential of polymer−small-molecule blends for triplet harvesting in organic light-emitting diodes (OLEDs) via thermally activated delayed fluorescence. The exciplex formed between poly(*N*-vinylcarbazole) (PVK) and 2,4,6-tris[3-(diphenylphosphinyl)phenyl]-1,3,5-triazine (PO-T2T) shows yellow-green emission and is applied in solution-processed OLEDs. The excellent film-forming properties in this blend allow easy spin coating and potential use in other solution-processing techniques, such as slot die coating. In this work, we critically address the reverse intersystem crossing mechanism in the presented exciplex system, including the role of local triplet states. Moreover, we bring a clear physical meaning to the decay components of the exciplex emission, including the decay occurring in a power-law fashion that is often ignored in the literature.




**KEYWORDS:** *OLED, TADF, exciplex, polymer, photophysics*

## INTRODUCTION

Since the fabrication of the first organic light-emitting diodes (OLEDs) by Tang and VanSlyke,[1] OLEDs have shown strong potential for application in lighting and display technologies.[2,3] The use of vacuum thermal evaporation (VTE)[4−6] is currently the method of choice in the fabrication of the most efficient OLEDs that are already in use in smart phones and television displays. However, because of the large material consumption, cost, and the need for spacious high-vacuum chambers and complicated shadow masks, VTE is likely to be used only in high-end applications, where high quality is favored over the production cost. Therefore, the objective of fabricating OLEDs at low cost directly from solution in large area remains alive. Techniques such as roll-to-roll, slot die, or inkjet printing can reduce material usage and costs associated with the long-standing aim of printing luminaires and displays. However, these techniques require preferably well-soluble materials with high molecular weight. Burroughes and co-authors[7,8] made the first polymer-based OLEDs. Since then, many polymers and dendrimers have exhibited their usefulness for application in OLEDs, and the development of such emitters is still ongoing.[9−14]

From the historical point of view, OLEDs started to be fabricated with purely fluorescent organic compounds, which were then superseded by more-efficient organic metal-complex emitters.[15] This breakthrough opened a pathway to increase exciton harvesting efficiency from 25% up to 100%. Nowadays, the metal complex emitters are being challenged by novel thermally activated delayed fluorescent (TADF) molecules and polymers, which also allow for 100% triplet harvesting.[16,17] Remarkably, without using platinum or iridium. Several TADF emitters have been reported in the literature, showing triplet-harvesting yields close to 100%,[15,18] including D-A3 molecular structures (one star-shaped donor with three acceptors attached to it) with multiple singlet−triplet state pairs.[19] TADFs have also been used as hosts for phosphorescent metal complexes.[20] Moreover, by using purely hydrocarbon hosts, Cui et al.[21] achieved nearly 100% exciton harvesting for both phosphorescent and TADF dopants. However, still no exciplex-based device realizing 100% exciton harvesting has been shown.[22]

Small-molecule TADF materials have been widely investigated to understand their photophysical and physicochemical properties; however, polymer-based and dendrimer materials,

Received: May 8, 2018
Accepted: July 25, 2018
Published: July 25, 2018





DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

which are more suitable for cost-efficient solution-processing methods, have been relatively neglected and solution-processed TADF devices remain elusive.

An interesting concept is to use commercially available or easy-to-synthesize donor and acceptor materials, which are not TADF on their own, but may form TADF exciplexes.[23−30] Such exciplex systems may show TADF properties, providing that proper energy alignment between the exciplex intermolecular charge-transfer state ($^1$CT) and the local triplet state ($^3$LE) is met.[5,26] In particular, we intend to find blends with high photoluminescence yield (PLQY) and good TADF properties. This requires solving a tradeoff between the energy alignment of the singlet CT and the local triplet $^3$LE states, to maximize reverse intersystem crossing (RISC), and suppressing the efficiency of the nonradiative decay rates.

Exciplex systems have been investigated mainly between small-molecule-based emitters, which are suitable for vacuum thermal evaporation or similar techniques, but not for solution-processing methods, since, typically, the fabrication of high-quality films with small molecules is very challenging, using solution processing methods. In contrast, TADF polymer-based exciplex systems allow for efficient triplet harvesting and are suitable for inkjet and slot die printing. In this work, we explore a polymer−small-molecule blend to obtain efficient TADF, using the formation of intermolecular exciplex states between the polymer PVK, acting as the electron donor, and the small molecules PO-T2T, acting as the electron acceptor unit (see Figure 1). This blend can be easily processed from solution and, to the best of our knowledge, is the first attempt to produce a polymer−small-molecule exciplex, for the purpose of strong TADF emission. Because of the prominent film-forming properties of poly(*N*-vinylcarbazole),[31,32] the blend can potentially be used in inkjet or slot-die printing. 2,4,6-Tris[3-(diphenylphosphinyl)phenyl]-1,3,5-triazine (PO-T2T),[25] which is used as an acceptor, shows excellent solubility in toluene, which helps in the formation of high-quality films.

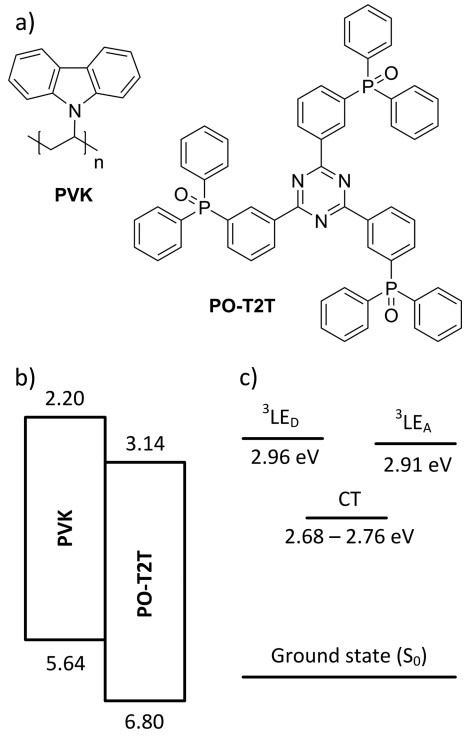



**Figure 1.** (a) Structures of donor (PVK) and acceptor (PO-T2T) materials used in this work; (b) schematic diagram of electronic energy levels of the donor and acceptor molecules in ground state; (c) excited-state energy diagram of the exciplex blend. $^3$LE$_D$ and $^3$LE$_A$ denote the triplet states localized on the donor and the acceptor, respectively.

## RESULTS AND DISCUSSION

Excited-state intermolecular charge transfer (CT) complexes (exciplexes) are formed between electron donor and acceptor species only in the excited state.[33−35] Therefore, no ground-state interaction between the donor and acceptor species exist, and, the absorption spectrum of the blend is the sum of the donor's and acceptor's absorption (see Figure 2).

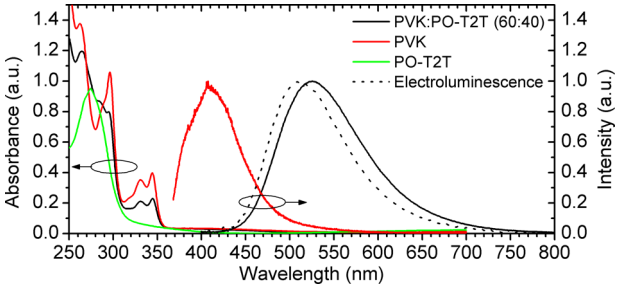



**Figure 2.** Absorption and photoluminescence (PL) spectra of donor, acceptor and the blend compared with device electroluminescence (EL) (for PL, $\lambda_{ex}$ = 355 nm). Note that PO-T2T shows no clearly detectable PL in neat film. Previous works show a very weak PL from PO-T2T film.[39]

The energy of the exciplex intermolecular CT state is roughly a function of the donor's ionization potential (IP$_D$) and the acceptor's electron affinity (EA$_A$).[34,35] These are usually identified as the HOMO$_D$ and LUMO$_A$ energies, respectively.[36,37] The formation of the exciplex leads to an emission spectrum that is significantly red-shifted, relative to donor and acceptor emissions. In the case of poly(*N*-vinylcarbazole) (PVK), IP$_D$ = 5.64 eV,[38] and PO-T2T, EA$_A$ = 3.14 eV,[25] this can clearly be seen in Figure 2. PVK shows weak blue emission, and the PO-T2T emission is too weak to be recorded. However, the blend of these two materials shows strong green CT photoluminescence (PL) ($\Phi_{PL}$ = 0.12 ± 0.02 in air and $\Phi_{PL}$ = 0.20 ± 0.03 in nitrogen).

Since the PVK:PO-T2T blend possesses prominent luminescent properties and shows TADF, it is therefore an ideal candidate for use in OLEDs as the emitting layer. These two materials are highly soluble in toluene. In particular, when low-molecular-weight PVK is used in the blend, high-molecular-weight PVK (PVKH) can then be used as the hole-transport/electron-blocking layer, which helps to improve device peformance.[40,41] PO-T2T is also used as an electron-transport/hole-blocking layer. However, electron transport and injection layers and cathode are evaporated, but all other layers are solution-processed. This leads to the following device structure: ITO | HIL 1.3N (45 nm) | PVKH (10 nm) | PVK:PO-T2T (60:40) (*x* nm) | PO-T2T (50 nm) | LiF (0.8 nm) | Al (100 nm), where *x* = 0 (Dev 4), 6 ± 1 (Dev 3), 16 ± 2 (Dev 2), and 27 ± 2 nm (Dev 1) (see Figure 3a, Figures S5−S11 in the Supporting Information, and Table 1).


DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

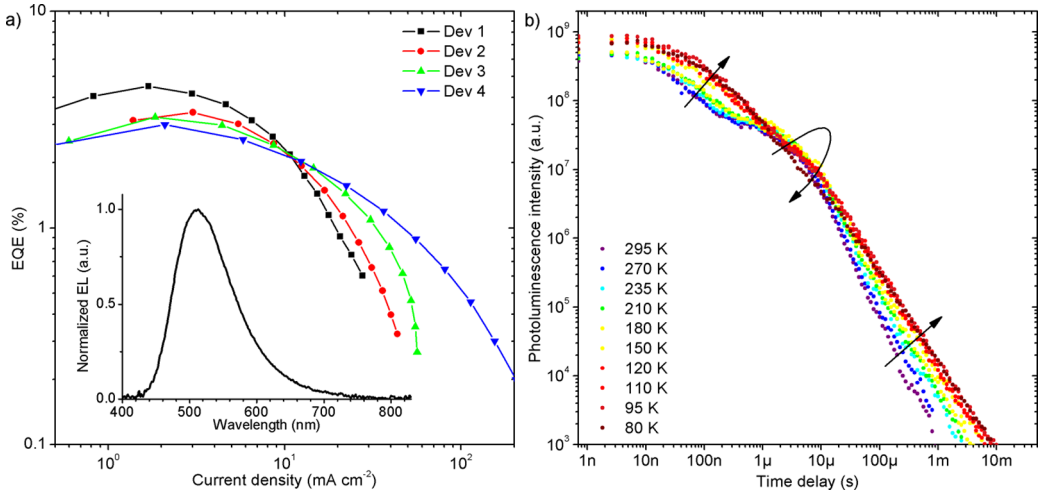



**Figure 3.** (a) EQE versus current density characteristics of OLEDs; inset shows EL spectrum of Dev 4. (b) Photoluminescence decay of PVK:PO-T2T exciplex at various temperatures ($\lambda_{ex}$ = 355 nm).

**Table 1. Characteristics of OLED Devices**

| device | $x^a$ (nm) | turn-on voltage, $V_{ON}$, at 1 cd m$^{-2}$ (V) | maximum EQE / EQE at 10 mA cm$^{-2}$ (%) | maximum current efficiency / current efficiency at 10 mA cm$^{-2}$ (cd A$^{-1}$) |
|---|---|---|---|---|
| Dev 1 | 27 ± 2 | 4.9 | 4.5/2.3 | 13.3/6.8 |
| Dev 2 | 16 ± 2 | 4.4 | 3.4/2.2 | 10.0/6.5 |
| Dev 3 | 6 ± 1 | 3.7 | 3.3/2.2 | 9.8/6.5 |
| Dev 4 | 0 | 2.6 | 3.0/2.1 | 9.3/6.3 |

[a]Device structure: ITO | HIL 1.3N (45 nm) | PVKH (10 nm) | PVK:PO-T2T (60:40) ($x$ nm) | PO-T2T (50 nm) | LiF (0.8 nm) | Al (100 nm).

A PVK:PO-T2T ratio of 60:40 was used to allow for sufficient hole and electron transport properties of the emissive layer and also to reduce the recombination at the PVKH interface. It is later presented that a variation in the PVK:PO-T2T ratio does not affect the CT state, and only a large disproportion between donor and acceptor (such as 1:99) can cause a significant local state emission (see Figures S1 and S2 in the Supporting Information).

Variation of the emissive layer thickness allows for control of the current density and turn-on voltage ($V_{ON}$). The device with the thickest emissive layer (Dev 1) shows the highest EQE (4.5%). In contrast, the lowest turn-on voltage ($V_{ON}$ = 2.6 V) and the highest maximum brightness is observed in Dev 4, which uses no blend donor−acceptor emissive layer ($x$ = 0 nm). In this case, the recombination occurs at the PVKH | PO-T2T interface. Interestingly, the electroluminescence (EL) spectrum is not affected by the emissive layer thickness or by the molecular weight of the donor material, and all devices (Dev 1−Dev 4), show similar EL spectrum at maximum brightness (see Figure S5 in the Supporting Information). Generally speaking, thin devices provide better charge conductivity; thus, the observed current densities increase significantly from Dev 1 to Dev 4. This is caused by the relatively low conductivity of the PVK:PO-T2T blend (more likely due to the low hole mobility of PVK itself); thus, a thin layer provides less resistance. As a result, devices with thicker PVK:PO-T2T layer show lower brightness than devices with thinner or no PVK:PO-T2T layer (Dev 4). Reducing the thickness slightly affects the charge balance, decreasing the maximum EQE of Dev 2−Dev 4, relative to Dev 1, but in contrast, the change in current density is much more pronounced. The variation in the optical turn-on voltage between Dev 1−Dev 4 is again caused by the low conductivity of PVK. Thinner PVK:PO-T2T layer provides larger current density at lower driving voltage, thus the 1 cd m$^{-2}$ brightness threshold is achieved at lower $V_{ON}$.

The EL spectrum is slightly blue-shifted, relative to the PL (Figure 2). Further examination of the EL spectra under various driving voltages (Figures S6−S9 in the Supporting Information) shows that a small blue-shift in the spectrum (affecting both the peak and the *onset*) upon increasing the voltage can be observed. This is more clearly seen in Dev 4 than in the other cases, while in the thickest device (Dev 1), this can hardly be observed. This effect is very likely to be caused by the electric field, changing the CT energy of the emissive species, as reported previously by Al-Attar et al.[42] While the blue-shift caused by the electric field shows a maximum amplitude of ∼7 nm (at the peak), the shift between EL and PL is ∼13 nm (at the peak). This observation shows that the electric field may be an important, but not the only, cause of the shift between PL and EL. This also suggests that the PL and EL may show different contributions of the time-resolved emissive components, i.e., the contribution of the most red-shifted power law emission in PL may not be present in the EL.

Less device efficiency roll-off is observed on devices with thin or no PVK:PO-T2T layer (Dev 3 and Dev 4) than in those with thicker EML (Dev 1 and Dev 2) (see Figure 3a). The actual mechanism causing the roll-off on device efficiency is still not clear and may be caused by a superposition of many different processes. Therefore, this is a very complex issue.[43] However, on the basis of some of our observations, possible major mechanisms can be proposed to explain the behavior of Dev 1−Dev 4. First, the thicker EML allows more space for the recombination zone to spreadout, which is more likely to move upon changing the applied voltage. This may lead to unfavorable charge balance at higher driving voltage, leading to a decrease in EQE. In the thin devices (Dev 3 and Dev 4), the recombination zone is either tightly localized between the PVKH and PO-T2T layers or is basically related to the PVKH/PO-T2T interface and is not likely to shift easily. As a consequence, there is little or no change of the charge balance in those devices at higher applied voltage. Second, triplet−


DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

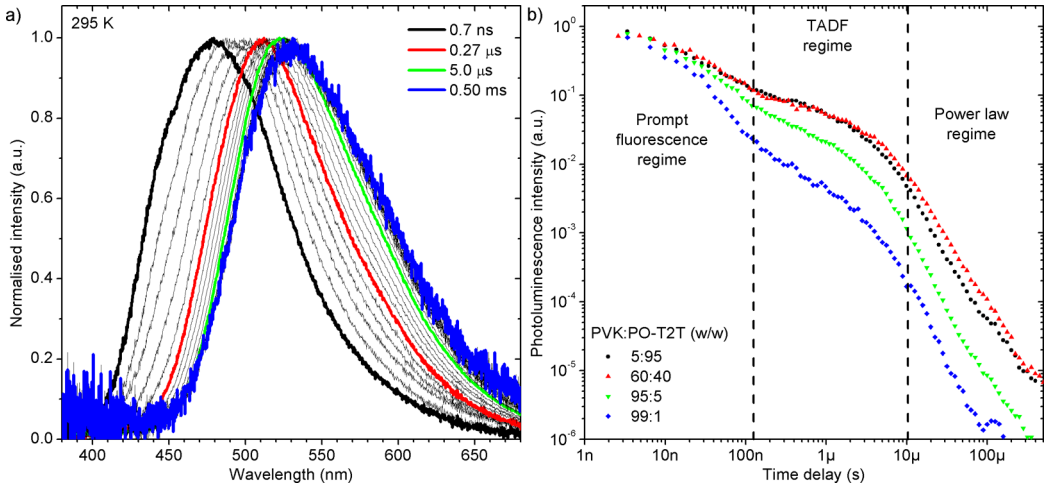



**Figure 4.** (a) Time-resolved PL spectra of PVK:PO-T2T (60:40) exciplex blend at 295 K. (b) Photoluminescence decay of PVK:PO-T2T blends at 295 K with various donor−acceptor ratio ($\lambda_{ex}$ = 355 nm).

triplet annihilation (TTA) and charge trapping phenomena are less likely to appear in thinner layers or at the interface. Thus, TTA-related roll-off is more pronounced in Dev 1 and Dev 2 than in Dev 3 and Dev 4.

The EQE value of 4.5% achieved in Dev 1 is a result of triplet harvesting by the TADF mechanism. Considering the $\Phi_{PL}$ = 0.20 ± 0.03, the EQE achieved in Dev 1 is close to the physical limit (see section S4 in the Supporting Information). Therefore, if TADF was not involved in the EL produced in this OLED, the EQE would only reach ∼1%−1.5%. This assuming an outcoupling factor of ∼0.2−0.3. Although the EQE remains below the values reported for vacuum-deposited small-molecule TADF emitters, these proof-of concept devices already open a pathway for future research, which may lead to more efficient solution-processed devices. PVK has been found to possess many trapping sites, which may, in fact, quench some of the emissive excitons;[44] therefore, new exciplex-forming polymers must be developed to possibly improve the EQE.

Time-resolved photophysical analysis of the PVK:PO-T2T luminescence reveals that the exciplex emission shows two exponential components, followed by a power-law emission (see Figure 3b, as well as Figure S12 in the Supporting Information). The first exponential component is the short-lived prompt fluorescence ($\tau$ = 32 ± 1 ns), and the second exponential decay is the long-lived delayed fluorescence ($\tau$ = 2.9 ± 0.2 $\mu$s). The power-law emission is likely originated from nongeminate charge recombination of free carriers produced in the blend, as described in previous work.[45] This is discussed later in the text and in the Supporting Information. Interestingly, the PL of the exciplex is significantly affected by nonradiative decay. This is visible as an increase of prompt and delayed fluorescence emissions, between 295 K and 180 K, with decreasing temperature. However, in the temperature range from 180 K to 150 K, the delayed fluorescence intensity switches away from the trend observed at higher temperatures and starts to decrease with temperature, as it is normally expected for a thermally activated process. This behavior is related to the suppression of the RISC rate, with decreasing available thermal energy. The temperature dependence in this region down to 80 K is very small, suggesting a negligible (close to zero) singlet−triplet gap in the exciplex.

The exciplex time-resolved emission, collected using a gated iCCD camera, reveals the entire complexity of the excited-state dynamics in this system. The exciplex emission gradually red-shifts over time (Figure 4a), showing a rapid change between 0.7 ns and 270 ns, for both the *onset* and emission peak. This is an intermediate region between prompt and delayed fluorescence, and it shows the most significant spectral changes, which can be related to the relaxation of the exciplex geometry, i.e., due to changes in the distance between the donor and acceptor molecules, which affects CT character through the Coulombic factor. Further changes in the spectrum occur between 270 ns and 5 $\mu$s and are probably due to the emission appearing from multiple CT states, with slightly different energies. It appears that different CT states are formed between PO-T2T molecules and various polymer sites, as a function of their distance. This effect induces the energy distribution associated with the exciplex state that involves PVK and PO-T2T molecules located at different distances, as well as PVK states that involve different numbers of *N*-vinylcarbazole repeating units. Although a variation on the exciplex energy clearly exists, a dominant state is present as the TADF decay component can easily be fitted using a single exponential equation. This occurs probably because the RISC rate is slower than the energy relaxation of the CT state in the exciplex, i.e., the RISC occurs predominately from the most stable CT states. Therefore, we use the emission spectra from this region to estimate the relaxed CT energy, which is further discussed in the context of TADF. Note that the emission intensity in this time range shows a linear dependence with excitation power, which is indicative of the TADF mechanism (see Figure S4 in the Supporting Information).

The power-law decay that is observed from 5 $\mu$s to 10 $\mu$s onward follows the TADF emission (see Figure 3b, as well as Figure S12). Within this region, no significant changes in the emission spectrum are observed; however, the emission is different from the spectra observed during the TADF exponential regime. Therefore, the origin of the power-law delayed emission is clearly different from that of the TADF regime. We believe this power-law emission decay is not created by direct upconversion of triplet states, but rather from nongeminate charge recombination. This has been observed previously in exciplex blends[38,45] and is caused by the dissociation of some of the CT states formed in the exciplex,


DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

which, upon dissociation, migrate through the blend as free charge carriers, until recombination later occurs. Polymer-based exciplex blends may be even more likely to undergo this process than small molecules as the charges (i.e., holes or electrons) may be transported not only by hopping between the molecules (or between polymer chains), but also along the polymer backbone (via hopping between grafted carbazole units, not through the backbone itself). This power-law emission intensifies at lower temperatures, since the longer CT state lifetime under these conditions promotes charge dissociation. Moreover, the free carriers migrate slower and are less prone to nonradiative deactivation processes.

Interestingly, the local triplet levels of the molecules forming the exciplex: PVK ($T_1$ = 2.96 eV)[44] and PO-T2T ($T_1$ = 2.91 eV; see Figure S14 in the Supporting Information) are clearly above the CT energy, determined from the delayed fluorescence spectra in Figure 4a ($^1$CT = 2.68−2.76 eV). In contrast with intramolecular CT states, where a good energy alignment between CT and local triplets has been proposed to be key for efficient triplet harvesting,[5,46−49] in the case of intermolecular exciplexes, we find that an energy alignment where the $^3$LE is above or isoenergetic with the CT facilitates efficient TADF emission.[23,25,27,50−54] Recently, it has been suggested that the $^3$LE state plays a crucial role in the reverse intersystem crossing (RISC) mechanism when the $^1$CT lies above it or is isoenergetic with it.[5,17,26,47,55−57] It appears that the RISC mechanism in small TADF molecules clearly involves the mixing of local and CT triplet states ($^3$LE and $^3$CT), as it has been observed from the temperature-dependent studies of TADF in various intramolecular exciplexes. However, the situation in intermolecular exciplexes may be different. Here, the $^3$LE state clearly lies above the $^1$CT state by 0.15−0.23 eV, and it is less evident for the local triplets to be involved in the RISC process, at least in the way that is suggested by the current theory models. Especially, the $^3$CT → $^3$LE → $^1$CT involving an endothermic $^3$CT → $^3$LE upconversion to a higher local triplet state appears to be questionable in this case. The exciplex described here shows an energy difference of >0.15 eV between the $^1$CT and the $^3$LE of PO-T2T. This would clearly quench the TADF at 80 K if this gap was relevant. Instead, TADF is only slowed at this temperature, but can still be easily observed. Moreover, a vast majority of recently studied efficient TADF intermolecular exciplexes show that the CT states are located well below the triplets of the donor and acceptor moieties.[22,25,39] Therefore, we conclude that, for intermolecular exciplex systems, the most common energy layout is the one where the $^3$LE state lies above the $^1$CT, and where the involvement of the local triplet state in the RISC is unlikely. Previous studies suggested that the ISC and RISC processes due to spin−orbit coupling between pure singlet and triplet charge transfer states is forbidden.[5,47,56,57] However, in the case of intermolecular exciplexes, where negligible energy gap between $^1$CT and $^3$CT is achieved, hyperfine interactions might become predominant and originate RISC with negligible loss, as no low energy triplet exists below the CT states.

To further understand the properties of the investigated exciplex blend various D−A ratios have been studied (see Figure 4b, as well as Figures S1 and S2). Remarkably, the ratio between donor−acceptor does not affect exciplex emission at all. All blends show the same CT emission spectrum and lifetime. This is different from the previously observed dependence of the CT energy upon changing the donor−acceptor ratio.[23,27] However, if extremely large excess of PVK is used, this leads to inefficient local emission of the donor, which reduces the contribution of efficient exciplex emission. A similar situation may occur in devices, leading to recombination on the PVK, thus reducing EQE. This property shows that using various, but not extreme, PVK:PO-T2T ratios to optimize recombination in the device is a prominent strategy.

It was also found that, when using PVKH as the electron blocking layer (EBL), the optimal donor−acceptor ratio is close to a 60:40 mass ratio. However, if an additional EBL cannot be used because of technological limitations, then this ratio may be changed without any effect on photophysics (i.e., by increasing amount of PVK to reduce current leakage).

## CONCLUSIONS

A novel highly luminescent TADF exciplex has been demonstrated, analyzed, and applied in solution-processed devices. The work presents a novel concept of using polymer-based exciplex blends to obtain efficient TADF emission with good solution-processing properties, and potential use in practical low-cost applications. This opens a new pathway in the use of intermolecular exciplexes in commercial applications, but also paves the way for new fundamental research, regarding the RISC mechanism in these systems. We believe PVK:PO-T2T blend is only a first and not fully optimized example of such polymer-based exciplexes, and further development of new polymers as donors or acceptors will occur as natural consequence of the concept described in this work. We also show that a variation in the donor−acceptor ratio does not affect the CT state properties at all. However, extreme ratios such as 99:1 may lead to a decrease in exciplex formation efficiency and thereby cause strong local fluorescence. We also addressed the role of the local triplet states in the RISC mechanism in exciplexes, where the CT state lies below the $^3$LE. Our results show that local triplet states are likely not playing a dominant role in the reverse intersystem crossing mechanism in these blends and probably the RISC mechanism involves significant hyperfine interactions.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.8b07554.

Experimental methods, supplementary figures, and discussions (PDF)

## AUTHOR INFORMATION


### Corresponding Author

*E-mail: f.m.b.dias@durham.ac.uk.

### ORCID

Piotr Pander: 0000-0003-4103-4154

Przemyslaw Data: 0000-0002-1831-971X

Fernando B. Dias: 0000-0001-9841-863X


### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

P.P. and M.C. acknowledge the EU's Horizon 2020 for funding the EXCILIGHT project, under Grant Agreement No. 674990. P.D. acknowledges the Polish National Science Centre for funding (Grant No. 2017/25/B/ST5/02488). F.B.D. acknowl-



DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

edges the EPSRC for funding, under Grant No. EP/L02621X/1.

## REFERENCES

(1) Tang, C. W.; VanSlyke, S. A. Organic Electroluminescent Diodes. *Appl. Phys. Lett.* **1987**, *51* (12), 913−915.
(2) Geffroy, B.; le Roy, P.; Prat, C. Organic Light-Emitting Diode (OLED) Technology: Materials, Devices and Display Technologies. *Polym. Int.* **2006**, *55* (6), 572−582.
(3) Forrest, S. R. The Path to Ubiquitous and Low-Cost Organic Electronic Appliances on Plastic. *Nature* **2004**, *428* (6986), 911−918.
(4) Uoyama, H.; Goushi, K.; Shizu, K.; Nomura, H.; Adachi, C. Highly Efficient Organic Light-Emitting Diodes from Delayed Fluorescence. *Nature* **2012**, *492* (7428), 234−238.
(5) Dias, F. B.; Santos, J.; Graves, D.; Data, P.; Nobuyasu, R. S.; Fox, M. A.; Batsanov, A. S.; Palmeira, T.; Berberan-Santos, M. N.; Bryce, M. R.; Monkman, A. P. The Role of Local Triplet Excited States in Thermally-Activated Delayed Fluorescence: Photophysics and Devices. *Adv. Sci.* **2016**, *3*, 1600080.
(6) Data, P.; Pander, P.; Okazaki, M.; Takeda, Y.; Minakata, S.; Monkman, A. P. Dibenzo[ A,j ]Phenazine-Cored Donor-Acceptor-Donor Compounds as Green-to-Red/NIR Thermally Activated Delayed Fluorescence Organic Light Emitters. *Angew. Chem., Int. Ed.* **2016**, *55* (19), 5739−5744.
(7) Burroughes, J. H.; Bradley, D. D. C.; Brown, A. R.; Marks, R. N.; Mackay, K.; Friend, R. H.; Burns, P. L.; Holmes, A. B. Light-Emitting Diodes Based on Conjugated Polymers. *Nature* **1990**, *347* (6293), 539−541.
(8) Bradley, D. D.; Brown, A. R.; Burn, P. L.; Burroughes, J. H.; Friend, R. H.; Holmes, A. B.; Mackay, K. D.; Marks, R. N. Light Emission from Poly(p-Phenylene Vinylene): A Comparison between Photo- and Electro-Luminescence. *Synth. Met.* **1991**, *43* (1−2), 3135−3141.
(9) Yang, X.; Zhou, G.; Wong, W. Y. Recent Design Tactics for High Performance White Polymer Light-Emitting Diodes. *J. Mater. Chem. C* **2014**, *2* (10), 1760−1778.
(10) Cook, J. H.; Santos, J.; Al-Attar, H. A.; Bryce, M. R.; Monkman, A. P. High Brightness Deep Blue/violet Fluorescent Polymer Light-Emitting Diodes (PLEDs). *J. Mater. Chem. C* **2015**, *3* (37), 9664−9669.
(11) Li, C.; Nobuyasu, R. S.; Wang, Y.; Dias, F. B.; Ren, Z.; Bryce, M. R.; Yan, S. Solution-Processable Thermally Activated Delayed Fluorescence White OLEDs Based on Dual-Emission Polymers with Tunable Emission Colors and Aggregation-Enhanced Emission Properties. *Adv. Opt. Mater.* **2017**, *5* (20), 1700435.
(12) Murto, P.; Minotto, A.; Zampetti, A.; Xu, X.; Andersson, M. R.; Cacialli, F.; Wang, E. Triazolobenzothiadiazole-Based Copolymers for Polymer Light-Emitting Diodes: Pure Near-Infrared Emission via Optimized Energy and Charge Transfer. *Adv. Opt. Mater.* **2016**, *4* (12), 2068−2076.
(13) Auer-Berger, M.; Trattnig, R.; Qin, T.; Schlesinger, R.; Nardi, M. V.; Ligorio, G.; Christodoulou, C.; Koch, N.; Baumgarten, M.; Müllen, K.; List-Kratochvil, E. J. W. All-Solution-Processed Multilayer Polymer/dendrimer Light Emitting Diodes. *Org. Electron.* **2016**, *35*, 164−170.
(14) Higginbotham, H.; Karon, K.; Ledwon, P.; Data, P. Carbazoles in Optoelectronic Applications. *Disp. Imaging* **2017**, *2*, 207−216.
(15) Tao, Y.; Yuan, K.; Chen, T.; Xu, P.; Li, H.; Chen, R.; Zheng, C.; Zhang, L.; Huang, W. Thermally Activated Delayed Fluorescence Materials Towards the Breakthrough of Organoelectronics. *Adv. Mater.* **2014**, *26* (47), 7931−7958.
(16) Zhang, Q.; Tsang, D.; Kuwabara, H.; Hatae, Y.; Li, B.; Takahashi, T.; Lee, S. Y.; Yasuda, T.; Adachi, C. Nearly 100% Internal Quantum Efficiency in Undoped Electroluminescent Devices Employing Pure Organic Emitters. *Adv. Mater.* **2015**, *27* (12), 2096−2100.
(17) Nobuyasu, R. S.; Ren, Z.; Griffiths, G. C.; Batsanov, A. S.; Data, P.; Yan, S.; Monkman, A. P.; Bryce, M. R.; Dias, F. B. Rational Design of TADF Polymers Using a Donor-Acceptor Monomer with Enhanced TADF Efficiency Induced by the Energy Alignment of Charge Transfer and Local Triplet Excited States. *Adv. Opt. Mater.* **2016**, *4* (4), 597−607.
(18) Dias, F. B.; Penfold, T. J.; Monkman, A. P. Photophysics of Thermally Activated Delayed Fluorescence Molecules. *Methods Appl. Fluoresc.* **2017**, *5* (1), 012001.
(19) dos Santos, P. L.; Ward, J. S.; Congrave, D. G.; Batsanov, A. S.; Eng, J.; Stacey, J. E.; Penfold, T. J.; Monkman, A. P.; Bryce, M. R. Triazatruxene: A Rigid Central Donor Unit for a D-A 3 Thermally Activated Delayed Fluorescence Material Exhibiting Sub-Microsecond Reverse Intersystem Crossing and Unity Quantum Yield via Multiple Singlet-Triplet State Pairs. *Adv. Sci.* **2018**, *5*, 1700989.
(20) Wang, Y.-K.; Li, S.-H.; Wu, S.-F.; Huang, C.-C.; Kumar, S.; Jiang, Z.-Q.; Fung, M.-K.; Liao, L.-S. Tilted Spiro-Type Thermally Activated Delayed Fluorescence Host for ≈100% Exciton Harvesting in Red Phosphorescent Electronics with Ultralow Doping Ratio. *Adv. Funct. Mater.* **2018**, *28* (13), 1706228.
(21) Cui, L.-S.; Xie, Y.-M.; Wang, Y.-K.; Zhong, C.; Deng, Y.-L.; Liu, X.-Y.; Jiang, Z.-Q.; Liao, L.-S. Pure Hydrocarbon Hosts for ≈100% Exciton Harvesting in Both Phosphorescent and Fluorescent Light-Emitting Devices. *Adv. Mater.* **2015**, *27* (28), 4213−4217.
(22) Sarma, M.; Wong, K.-T. Exciplex: An Intermolecular Charge-Transfer Approach for TADF. *ACS Appl. Mater. Interfaces* **2018**, *10*, 19279.
(23) Li, J.; Nomura, H.; Miyazaki, H.; Adachi, C. Highly Efficient Exciplex Organic Light-Emitting Diodes Incorporating a Heptazine Derivative as an Electron Acceptor. *Chem. Commun.* **2014**, *50* (46), 6174−6176.
(24) Data, P.; Kurowska, A.; Pluczyk, S.; Zassowski, P.; Pander, P.; Jedrysiak, R.; Czwartosz, M.; Otulakowski, L.; Suwinski, J.; Lapkowski, M.; Monkman, A. P. Exciplex Enhancement as a Tool to Increase OLED Device Efficiency. *J. Phys. Chem. C* **2016**, *120* (4), 2070−2078.
(25) Hung, W.-Y.; Fang, G.-C.; Lin, S.-W.; Cheng, S.-H.; Wong, K.-T.; Kuo, T.-Y.; Chou, P.-T. The First Tandem, All-Exciplex-Based WOLED. *Sci. Rep.* **2015**, *4* (1), 5161.
(26) Dos Santos, P. L.; Dias, F. B.; Monkman, A. P. Investigation of the Mechanisms Giving Rise to TADF in Exciplex States. *J. Phys. Chem. C* **2016**, *120* (32), 18259−18267.
(27) Jankus, V.; Data, P.; Graves, D.; McGuinness, C.; Santos, J.; Bryce, M. R.; Dias, F. B.; Monkman, A. P. Highly Efficient TADF OLEDs: How the Emitter-Host Interaction Controls Both the Excited State Species and Electrical Properties of the Devices to Achieve Near 100% Triplet Harvesting and High Efficiency. *Adv. Funct. Mater.* **2014**, *24* (39), 6178−6186.
(28) Cherpak, V.; Gassmann, A.; Stakhira, P.; Volyniuk, D.; Grazulevicius, J. V.; Michaleviciute, A.; Tomkeviciene, A.; Barylo, G.; von Seggern, H. Three-Terminal Light-Emitting Device with Adjustable Emission Color. *Org. Electron.* **2014**, *15* (7), 1396−1400.
(29) Cherpak, V.; Stakhira, P.; Minaev, B.; Baryshnikov, G.; Stromylo, E.; Helzhynskyy, I.; Chapran, M.; Volyniuk, D.; Hotra, Z.; Dabuliene, A.; Tomkeviciene, A.; Voznyak, L.; Grazulevicius, J. V. Mixing of Phosphorescent and Exciplex Emission in Efficient Organic Electroluminescent Devices. *ACS Appl. Mater. Interfaces* **2015**, *7* (2), 1219−1225.
(30) Volyniuk, D.; Cherpak, V.; Stakhira, P.; Minaev, B.; Baryshnikov, G.; Chapran, M.; Tomkeviciene, A.; Keruckas, J.; Grazulevicius, J. V. Highly Efficient Blue Organic Light-Emitting Diodes Based on Intermolecular Triplet−Singlet Energy Transfer. *J. Phys. Chem. C* **2013**, *117* (44), 22538−22544.
(31) Jankus, V.; Abdullah, K.; Griffiths, G. C.; Al-Attar, H.; Zheng, Y.; Bryce, M. R.; Monkman, A. P. The Role of Exciplex States in Phosphorescent OLEDs with Poly(vinylcarbazole) (PVK) Host. *Org. Electron.* **2015**, *20*, 97−102.
(32) Kozhevnikov, V. N.; Zheng, Y.; Clough, M.; Al-Attar, H. A.; Griffiths, G. C.; Abdullah, K.; Raisys, S.; Jankus, V.; Bryce, M. R.; Monkman, A. P. Cyclometalated Ir(III) Complexes for High-Efficiency Solution-Processable Blue PhOLEDs. *Chem. Mater.* **2013**, *25* (11), 2352−2358.


DOI: 10.1021/acsami.8b07554
ACS Appl. Mater. Interfaces XXXX, XXX, XXX−XXX

(33) Song, L.; Hu, Y.; Liu, Z.; Lv, Y.; Guo, X.; Liu, X. Harvesting Triplet Excitons with Exciplex Thermally Activated Delayed Fluorescence Emitters toward High Performance Heterostructured Organic Light-Emitting Field Effect Transistors. *ACS Appl. Mater. Interfaces* **2017**, *9* (3), 2711−2719.
(34) Pander, P.; Kudelko, A.; Brzeczek, A.; Wroblowska, M.; Walczak, K.; Data, P. Analysis of Exciplex Emitters. *Disp. Imaging* **2017**, *2*, 265−277.
(35) *The Exciplex*; Gordon, M., Ware, W. R., Eds.; Academic Press: New York, 1975.
(36) Data, P.; Lapkowski, M.; Motyka, R.; Suwinski, J. Influence of Alkyl Chain on Electrochemical and Spectroscopic Properties of Polyselenophenes. *Electrochim. Acta* **2013**, *87*, 438−449.
(37) Świst, A.; Cabaj, J.; Sołoducho, J.; Data, P.; Łapkowski, M. Novel Acridone-Based Branched Blocks as Highly Fluorescent Materials. *Synth. Met.* **2013**, *180*, 1−8.
(38) Pander, P.; Bulmer, R.; Martinscroft, R.; Thompson, S.; Lewis, F. W.; Penfold, T. J.; Dias, F. B.; Kozhevnikov, V. N. 1,2,4-Triazines in the Synthesis of Bipyridine Bisphenolate ONNO Ligands and Their Highly Luminescent Tetradentate Pt(II) Complexes for Solution-Processable OLEDs. *Inorg. Chem.* **2018**, *57*, 3825−3832.
(39) Liu, X.-K.; Chen, Z.; Qing, J.; Zhang, W.-J.; Wu, B.; Tam, H. L.; Zhu, F.; Zhang, X.-H.; Lee, C.-S. Remanagement of Singlet and Triplet Excitons in Single-Emissive-Layer Hybrid White Organic Light-Emitting Devices Using Thermally Activated Delayed Fluorescent Blue Exciplex. *Adv. Mater.* **2015**, *27* (44), 7079−7085.
(40) Pashazadeh, R.; Pander, P.; Lazauskas, A.; Dias, F. B.; Grazulevicius, J. V. Multicolor Luminescence Switching and Controllable Thermally Activated Delayed Fluorescence Turn on/Turn off in Carbazole−Quinoxaline−Carbazole Triads. *J. Phys. Chem. Lett.* **2018**, *9* (5), 1172−1177.
(41) Cook, J. H.; Al-Attar, H. A.; Monkman, A. P. Effect of PEDOT−PSS Resistivity and Work Function on PLED Performance. *Org. Electron.* **2014**, *15* (1), 245−250.
(42) Al Attar, H. A.; Monkman, A. P. Electric Field Induce Blue Shift and Intensity Enhancement in 2D Exciplex Organic Light Emitting Diodes; Controlling Electron-Hole Separation. *Adv. Mater.* **2016**, *28* (36), 8014−8020.
(43) Murawski, C.; Leo, K.; Gather, M. C. Efficiency Roll-off in Organic Light-Emitting Diodes. *Adv. Mater.* **2013**, *25* (47), 6801−6827.
(44) Jankus, V.; Monkman, A. P. Is Poly(vinylcarbazole) a Good Host for Blue Phosphorescent Dopants in PLEDs? Dimer Formation and Their Effects on the Triplet Energy Level of poly(N-Vinylcarbazole) and poly(N-Ethyl-2-Vinylcarbazole). *Adv. Funct. Mater.* **2011**, *21* (17), 3350−3356.
(45) Kabe, R.; Adachi, C. Organic Long Persistent Luminescence. *Nature* **2017**, *550* (7676), 384−387.
(46) Data, P.; Pander, P.; Okazaki, M.; Takeda, Y.; Minakata, S.; Monkman, A. P. Dibenzo[ A,j ]Phenazine-Cored Donor-Acceptor-Donor Compounds as Green-to-Red/NIR Thermally Activated Delayed Fluorescence Organic Light Emitters. *Angew. Chem., Int. Ed.* **2016**, *55* (19), 5739−5744.
(47) Etherington, M. K.; Gibson, J.; Higginbotham, H. F.; Penfold, T. J.; Monkman, A. P. Revealing the Spin−vibronic Coupling Mechanism of Thermally Activated Delayed Fluorescence. *Nat. Commun.* **2016**, *7*, 13680.
(48) Gibson, J.; Monkman, A. P.; Penfold, T. J. The Importance of Vibronic Coupling for Efficient Reverse Intersystem Crossing in Thermally Activated Delayed Fluorescence Molecules. *ChemPhysChem* **2016**, *17* (19), 2956−2961.
(49) Santos, P. L.; Ward, J. S.; Data, P.; Batsanov, A. S.; Bryce, M. R.; Dias, F. B.; Monkman, A. P. Engineering the Singlet−triplet Energy Splitting in a TADF Molecule. *J. Mater. Chem. C* **2016**, *4* (17), 3815−3824.
(50) Jankus, V.; Chiang, C. J.; Dias, F.; Monkman, A. P. Deep Blue Exciplex Organic Light-Emitting Diodes with Enhanced Efficiency; P-Type or E-Type Triplet Conversion to Singlet Excitons? *Adv. Mater.* **2013**, *25* (10), 1455−1459.
(51) Graves, D.; Jankus, V.; Dias, F. B.; Monkman, A. Photophysical Investigation of the Thermally Activated Delayed Emission from Films of M-MTDATA:PBD Exciplex. *Adv. Funct. Mater.* **2014**, *24* (16), 2343−2351.
(52) Hung, W.; Wang, T.; Chiang, P.; Peng, B.; Wong, K. Remote Steric Effect as a Facile Strategy for Improving the Efficiency of Exciplex-Based OLEDs. *ACS Appl. Mater. Interfaces* **2017**, *9* (8), 7355−7361.
(53) Liu, W.; Chen, J.-X.; Zheng, C.; Wang, K.; Chen, D.; Li, F.; Dong, Y.-P.; Lee, C.-S.; Ou, X.-M.; Zhang, X.-H. Novel Strategy to Develop Exciplex Emitters for High-Performance OLEDs by Employing Thermally Activated Delayed Fluorescence Materials. *Adv. Funct. Mater.* **2016**, *26* (12), 2002−2008.
(54) Kim, K.-H.; Yoo, S.-J.; Kim, J.-J. Boosting Triplet Harvest by Reducing Nonradiative Transition of Exciplex toward Fluorescent Organic Light-Emitting Diodes with 100% Internal Quantum Efficiency. *Chem. Mater.* **2016**, *28* (6), 1936−1941.
(55) Etherington, M. K.; Franchello, F.; Gibson, J.; Northey, T.; Santos, J.; Ward, J. S.; Higginbotham, H. F.; Data, P.; Kurowska, A.; Dos Santos, P. L.; Graves, D. R.; Batsanov, A. S.; Dias, F. B.; Bryce, M. R.; Penfold, T. J.; Monkman, A. P. Regio- and Conformational Isomerization Critical to Design of Efficient Thermally-Activated Delayed Fluorescence Emitters. *Nat. Commun.* **2017**, *8* (April), 14987.
(56) Lim, B. T.; Okajima, S.; Chandra, A. K.; Lim, E. C. Radiationless Transitions in Electron Donor−acceptor Complexes: Position-dependent Deuterium Isotope Effects on S 1 → S 0 Internal Conversion of 1:1 and 2:1 Complexes of Methyl-substituted Benzenes with Tetracyanobenzene. *J. Chem. Phys.* **1982**, *77* (8), 3902−3909.
(57) Marian, C. M. Mechanism of the Triplet-to-Singlet Upconversion in the Assistant Dopant ACRXTN. *J. Phys. Chem. C* **2016**, *120* (7), 3715−3721.


DOI: 10.1021/acsami.8b07554
*ACS Appl. Mater. Interfaces* XXXX, XXX, XXX−XXX